TECHNICAL MEMORANDUMS

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No. 458

STEEL SPARS

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S T E E L   S P A R S.*

By Brian L. Martin.

Although the idea of constructing aircraft of metal is an old one, the all-metal aircraft industry in this country as we know it to-day can be said to have started in 1916. Owing to the shortage of timber suitable for airplane spars, the Aeronautical Supplies Department initiated a competition in 1918 open, apparently to anybody interested, for the design of metal spars to replace wooden ones. It is not proposed to deal with these metal spars in detail, as this has been done before. Various papers have been read on the subject, one of the best being by the late Major Nicholson to the Institution of Engineers and Shipbuilders in Scotland, in 1920.

Before going on to give a brief summary of the experience gained from these early spars, it would be well, perhaps, to say a word on the Steel Wing Company in its early days. Prior to the competition mentioned above, Mr. D. J. Mooney had purchased what were probably the earliest patents in connection with the construction of aircraft in metal taken out in this country. The Steel Wing Company was formed in order to develop these patents; and such progress had been made that by the time of the competition this firm was not only able to produce a metal spar,

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but had already produced a set of metal wings for a Bristol airplane and was manufacturing on production lines complete B.E.2.D. all-metal wings. It would appear that the ideal underlying the competition was the production of composite wings, wings with metal spars and wooden ribs, the material for the latter being readily obtainable from wood unsuitable for spars. The production of all-metal wings at this early stage, although not required by the competition, put the Steel Wing Company in a very favorable position; and the development of their spars from the girder type to the box type led to the production of the forms of steel spars which are in general use to-day.

The earliest metal spars were mainly of the bridge or built-up girder type; then came designs derived from I beams, and lastly, box spars.

The girder type consisted of four booms connected vertically and horizontally by some sort of lattice bracing. Sometimes the two top and the two bottom booms were connected by a wider section instead of lattice bracing where extra strength was required; sometimes the wider sections only formed the booms.

These spars were inefficient because it was not realized that from a consideration of the loads imposed on them, airplane spars are in a class by themselves. On the one hand are bridges and girders, which have to withstand bending little, if any, end load being imposed on them, and on the other, stanchions, which have to stand up to the large end load with comparatively little

bending. Both these types of structure are admirably adapted to the conditions for which they were designed, but neither is particularly suitable for an airplane spar, which has to withstand a large amount of bending, together with a large end load.

The stress distribution curve due to bending only for a solid symmetrical spar is shown in the diagram by line Aa. The addition of end load causes the curve to be shifted bodily to the right to Bb, indicating an increase of compressive stress, assuming a compressive end load, which is usual. In practice a second modification is necessary, due to the end load-deflection bending moment, which is an addition to the original bending moment, the resultant curve being indicated by Cc. This shows how conditions of loading for an airplane spar accentuate the compressive stresses, and the main difficulty in designing an airplane spar, especially metal, is to make the spar section withstand these combined stresses successfully.

The stress distribution is somewhat different in the case of girder type spars. In these the flanges resist the bending while the webs resist the shear load only. The moment and its increment due to deflection are resisted by a couple consisting of a compressive load in one flange and an equal tensile load in the other, the arm being the distance between the centers of gravity of the flanges. Owing to the flange sections being usually shallow, as will be shown later, these loads are to all intents uniformly distributed over the sections, and as shown above, the compression load is increased and the tensile load

decreased by half the end load.

The flanges of the girder type of spar made up of thin gauge angles or channels and flattish plates, were ill adapted to resist compression stresses on account of the unsupported free edges and also of the large amount of flat, or comparatively flat surfaces. A simple experiment with a piece of paper will demonstrate this point. A piece of foolscap held with the long sides vertically will not support its own weight normally, but if the paper be curved with the fingers, not only will it be self-supporting, but it will also withstand an appreciable amount of end load. It will be noticed that failure will take place by the buckling of the vertical edges of the paper. In view of this it will be appreciated that the size of the flange angles or channels for a given thickness of material is very limited both as regards breadth and depth. Hence flanges made like this were relatively shallow. In the case of a flange made of two angles or channels connected by some sort of plate, there would be six free edges all situated in a region of high stress, any one of which might give prematurely owing to slight buckling due to riveting or other manufacturing defect, thereby causing the whole flange to go. It was found that this type of flange almost invariably failed between the points of attachment of the web bracing, and that failure was accelerated by excessive deflection sidewise due to the small moment of inertia laterally, inherent in this design.

This form of spar was inefficient also on account of the small stress which could be developed. A channel formed from thin strip will not develop under end load a greater stress than approximately half that which the metal is capable of developing.

It may be said that the free edges could have been stiffened by beading; but in order to stiffen the flange as a whole the bead would have to be so large that it would probably have interfered seriously with the attachment of web bracing.

This form of spar has certain very obvious advantages, i.e., it can easily be made tapered so that it can follow the contour of a tapered cantilever wing; and the attachment of ribs and fittings is easy and can be done very neatly. In view of this, it is satisfactory to state that in one of the latest developments of this type, the disadvantages of the earlier examples mentioned previously, have been surmounted. The top and bottom flanges each consist of a single deeply corrugated rolled section which is efficient from a stress point of view and which appears to be well adapted to jigging.

Of the I beam type of spar there are not many examples. In one of the earliest the flange consisted of a corrugated oval section formed from mild steel strip, with flanged edges, which were riveted or welded to a single corrugated web. In some respects this was a very sound design. The flanges as well as the free edges were supported along their whole length, and the free edges were well removed from the region of maximum stress. The disad-

vantages are in manufacture. The flange section would be difficult to form in high tensile steel; it would be very difficult to get the flanged edges close up to one another; it would be difficult to assemble the flanges and webs for riveting accurately and easily; and one can see difficulty in the attachment of fittings. This particular spar was very small, and it was possible to make each flange from one strip. Later and bigger spars of this type had built-up flanges, but these introduced two further difficulties; at least six rows of rivets were necessitated and side supports were required to make the spar stable. Such supports could be made part of the rib structure, but the difficulty of attaching fittings would remain.

The built-up box type of spar will be dealt with after tracing the evolution of the Steel Wing Company's spars.

A word may be said here on the subject of solid drawn tubular spars. Spars have been made of solid drawn tubes of circular, rectangular, oval, and corrugated oval sections. The production of these special section tubes is not in itself difficult so long as the tube is of uniform thickness round its circumference. What is difficult is a) grading the thickness circumferentially so as to get the greatest thickness at the points of maximum stress and so get an economical section; and b) hardening the tubes, which must be soft for drawing. This almost invariably considerably distorts the tube.

Further, the attachment of ribs and fittings is apt to be

more difficult in practice than would appear to be the case at first sight. These remarks apply chiefly to tubular spars intended for wing spars. They are better adapted for use as aileron and elevator spars, where torsional strength is of paramount importance.

It will be seen from the foregoing remarks that the desiderata of a metal spar, apart from such obvious points as adequate strength, light weight and stiffness, are as follows:

(a) The free edges of the sections formed from strip should be removed as far as possible from the region of high stress.

(b) They should be shaped in such a way that they will stand a sufficient amount of compressive stress (taking (a) into account) to allow the section to develop the maximum stress possible.

(c) The flanges should be efficiently supported throughout their entire length.

(d) The flanges and webs should be shaped so that their assembly for attaching is easy and foolproof.

(e) The rivets or other form of attachment should be easily accessible.

(f) The shape of the spar should be such that the attachment of ribs, and more particularly strut fittings, present no excessive difficulties.

The first of the Steel Wing Company's spars made in 1916 and used in a B.E.2.C. wing consisted of four unequal legged

high tensile steel channels forming the two flanges. These (Fig. 2) were separated by vertically corrugated webs of aluminum riveted to the long legs of each channel, the rivets serving to hold the two halves of the spar together.

This suffered from the defects inherent in any form of channel flange, but was better than some designs, as the long free edges of the channels were rigidly supported at fairly close intervals.

It will be noticed that this spar conforms to some of the desiderata enumerated above, namely, in the assembly of the various parts which could hardly be simpler; in that the riveting presents no great difficulties; that the attachment of ribs and fittings is straightforward; and further, if desired the spar could be made lopsided so as to conform more closely to the rib contour. The most obvious objection is its weakness laterally; and the first attempt to improve this consisted of separating the two halves by means of spacers at intervals. In this form the legs of the channel flanges were made equal, as each half could be riveted up separately. The next development was an attempt to improve the strength of the spar by modifying the flanges as in Figure 2 (a), but this hardly got beyond the experimental state owing to the difficulty of riveting. Later, the halves of the spar were connected by two strips with transverse corrugations at intervals to act as struts, with the intervening metal stamped out to form double diagonal bracing, as

shown in Figure 2. Figure 3 shows how the flanges were doubled at the most highly stressed parts of the spar, and in the particular one shown the edges of the channels were beaded.

So far the spars had followed the subject matter of the original patents fairly closely. One deviation, not illustrated, was to make the web corrugations oblique instead of vertical corresponding corrugations in each half of the spar being inclined to each other. Another was to make successive corrugations in the same web inclined to each other so as to form a kind of lattice bracing. None of these modifications led very far.

In looking at the first three illustrations it will be obvious that roughly only half of the material in the spar was used to resist the biggest loads on the spar, namely, end load and bending. The remainder was used to counteract the shear load which is relatively small. This was a great waste of material, as the horizontal bracing was very inefficient owing to the fact that the bracing on the compression side became slack, and therefore inoperative. The web was far too stiff in view of the small shear load it had to take and was inefficient as regards longitudinal strength.

Figure 4 shows the first effective method of making the web more efficient. One of the channel flanges has been absorbed into the web, thus making it contribute towards the longitudinal strength while the form of top and bottom bracing has evidently been the inspiration for the method of dealing with the

center of the web. It will be noticed that this form of construction still maintains the easy assembly, easy riveting, and easy attachment of fittings of the earliest forms.

So far one of the inefficient members has been improved, and in Figure 5 it will be seen that the ineffective lateral bracing and the remaining channel flange has been replaced by a longitudinally corrugated strip with beaded edges, all of which contributes towards the longitudinal strength. This form of flange is probably as good as, if not better than, the old form in resisting lateral bending, while being very much easier to produce, since it could be rolled continuously instead of having a series of intermittent piercing and bumping operations performed on it.

Some consideration such as this must have suggested the use of a Figure 5 flange and Figure 5 web without its perforations and beads, as shown in Figure 6. This was tried purely as an experiment, but it soon became evident that the large flat on the web would give trouble, although it was a big advance from a production point of view. This was improved as shown in Figure 7 by deepening the main corrugation on the flange, thereby making it more effective and relieving the web of some load. An additional pair of corrugations was introduced into the web, which reduced the width of the flat considerably.

Figure 8 is merely a modification of Figure 7 with all the flats eliminated, thereby making the whole of the spar section

effective in resisting end load and bending. It was found that the inherent stiffness of the longitudinally corrugated web was sufficient to withstand shear load. It was realized at this stage that the free edges of the sections were comparatively close to the region of maximum stress, a fault which was overcome by raising the center corrugation above the curved edges as shown in Figure 9, thereby making the flange deeper, and so more effective. A spar like this developed under bending and small end load a maximum stress quite comparable with that obtainable from the material of which it was composed.

The development of these spars has now been traced from the substantially girder type to a box type with the sides suitably corrugated to resist compressive stress. Under very heavy end load conditions it is found that the webs of this latter type tend to wave longitudinally. This is due to insufficient depth of corrugation, and could be corrected by deeper corrugations were it not for the fact that if the tangents to the web section at points where the curvature changes from, say, convex outwards to convex inwards, or vice versa, are horizontal, the web is unduly weak in shear, which causes an abnormally large deflection, and consequently a large addition to the compressive stresses.

These webs, therefore, have to be supported by transverse diaphragms in bays where the end load is great. Another method of preventing the webs from waving which has been used successfully,

is to bring the webs together and attach them to one another at the center. This is quite effective for preventing waving, but it is believed that the fact of the edges of the web overhanging the center causes it to be weak in shear, thereby causing large deflections.

A second alternative consists of leaving the center half of the web quite flat, and punching large circular holes along this flat, the holes in one web being opposite the holes in the other. Very thin tubes are made with bumps or crinkles near the ends as in Figure 9a, the distance between the bumps being equal to the distance between the flats on the webs. The normal outside diameter of the tubes is the same as that of the holes in the webs, into which the ends of the tubes are pushed and the edges beaded over. This is quite effective in resisting waving, but one would imagine that the center portion of the web, together with the tubes, is inefficient as regards longitudinal strength as well as expensive to produce.

The simple form of box spar at which we have arrived is limited in size by two considerations (a) the ability of a corrugated strip to withstand compressive stresses without the addition of extra stiffeners at intervals, representing wasted weight, and (b) the fact that it is difficult to obtain high tensile steel strip wider than 6 inches or $6\frac{1}{2}$ inches. Strip of a greater width than this is seldom sufficiently flat to be satisfactory.

When designing spars more than $3\frac{1}{2}$ inches or 4 inches deep,

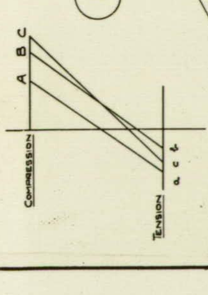
the question of web stability becomes very urgent. The webs can be brought together at the centers, but this form absorbs more material than a flat web, and does not lead one much further. One way in which this problem has been successfully tackled is shown in Figure 10. This spar is 6 inches deep, and the webs support each other by being connected by two longitudinal diaphragms, which can be quite light, and which, in addition to stiffening the webs, contribute towards the longitudinal strength of the spar. Figure 11 shows a development of this idea for an 8-inch spar. The webs are extended by means of trough-shaped sections which also function as longitudinal diaphragms and to which the flanges are connected.

Earlier in this paper the girder type of spar was adversely criticised, but it should be mentioned that this type has certain very obvious advantages; i.e., it can easily be made tapered, so that it can follow the contour of a tapered cantilever wing; and the attachment of ribs and fittings is easy and can be done very neatly. On the other hand, it has certain inherent defects, which have been dealt with. It may well be that the girder type of spar will be of great use in the future if and when really large spars are required; spars, that is to say, whose depth is measured in feet instead of inches. Box spars of this size made of corrugated strip would present very great difficulties. Even if high tensile steel strip wider in proportion could be obtained, it is difficult to see how the necessarily large expanses of thin

corrugated metal, both vertical and horizontal, could be adequately and economically stiffened. Failing a resort to the girder type, the solution of the problem of the giant spars of the future, if required, appears to call for the evolution of an entirely new form of spar construction, unless the design of this wing structure is radically altered.

The development of the Steel Wing Company's spars has now been traced up to the year 1925. Experiments are now being carried out with a form of box spar which is fundamentally different from those already described. This, it is hoped, will be the subject of another paper.

Many readers of this paper are probably aware that the amalgamation of the Steel Wing Company with the Gloster Aircraft Company is now an accomplished fact. The cooperation of two firms with such different specialized knowledge and experience cannot but produce a combination well adapted to turn out up-to-date aircraft entirely of metal through one supplying the deficiencies of the other. Their different outlook will enable each to criticise the other's proposals from the aerodynamic as well as from the constructional point of view, and by modifying these proposals, to produce a completed article which is advantageous to both. Mutual criticism and pooling of ideas are very stimulating to the production and development of new ideas, and by cooperation on these lines the amalgamation should prove a happy and beneficial one to all concerned.



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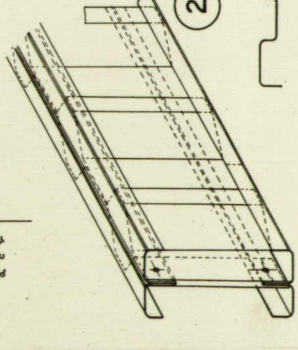

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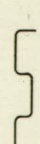

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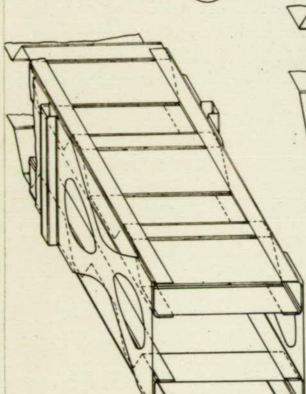

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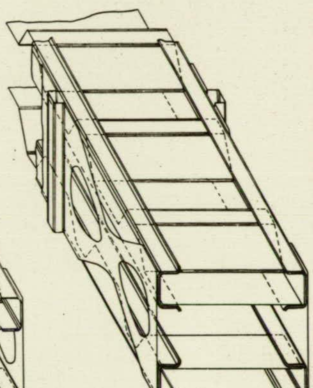

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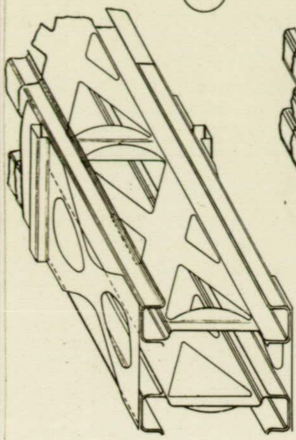

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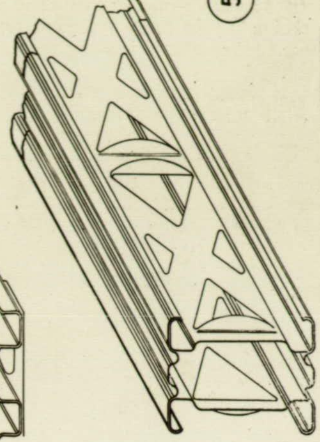

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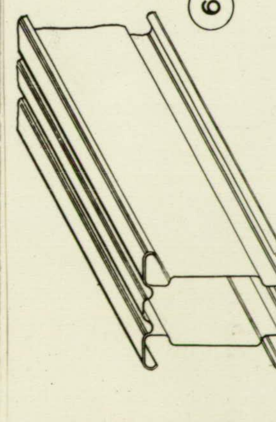

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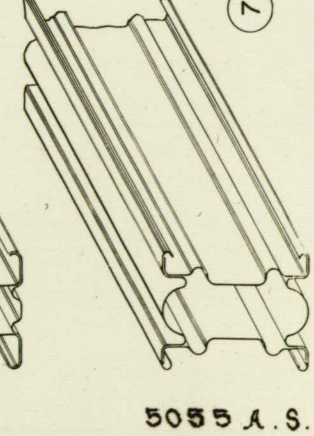

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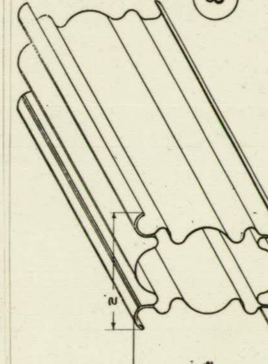

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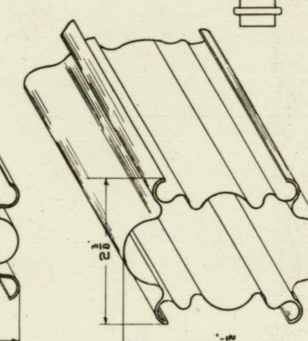

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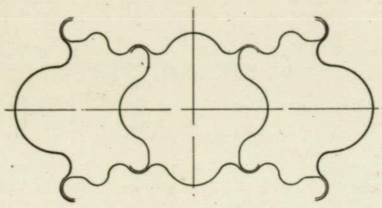

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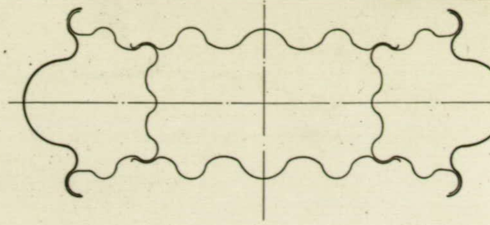

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